Retention of Quality and Nutritional Value of 13 Fresh-Cut Vegetables Treated with Low-Dose Radiation

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ABSTRACT: Improving the microbial safety while maintaining quality of fresh fruits and vegetables will increase consumer confidence in fresh produce. This study was conducted to investigate the effects of irradiation at 1 kGy, a dose that potentially inactivates *E. coli* O157:H7 by 5 logs, on the quality of 13 common fresh-cut vegetables: iceberg, romaine, green and red leaf lettuce, spinach, tomato, cilantro, parsley, green onion, carrot, broccoli, red cabbage, and celery. The results showed that the appearance of irradiated samples was similar to the nonirradiated ones except that irradiated carrots, celery, cilantro, and green onions had higher appearance scores than corresponding nonirradiated vegetables. There was no difference in the instrumental texture between irradiated samples and nonirradiated ones. The aroma of several irradiated vegetables was significantly better than controls after 14-d storage, because these control samples decayed or senesced. The 1 kGy irradiation did not affect vitamin C content of most vegetables; however, irradiated green and red leaf lettuce had 24% to 53% lower vitamin C contents than the controls. Our results suggest that most fresh-cut fruits and vegetables tested can tolerate up to 1 kGy irradiation without significant losses in any of the quality attributes.

Keywords: appearance, aroma, fresh-cut vegetables, irradiation, texture, vitamin C

Introduction

Consumers are strongly encouraged to eat more produce for their well-known benefits. Unfortunately, in recent years, there has been an increase in the number of outbreaks and recalls associated with consumption of fresh produce due to contamination with human pathogens such as *Escherichia coli* O157:H7. Between 1996 and 2006, there were more outbreaks of foodborne illnesses associated with fresh produce than any other categories of foods (Smith 2007). Of these produce related outbreaks, 25% were associated with fresh-cut produce. Although the reasons for this increase in fresh produce-related foodborne illnesses are not fully understood, centralized processing plants with wide distribution, an increase in global trade, a longer food chain, an increase in produce consumption, and an aging population that is susceptible to foodborne illness all may play a role (FDA 2001). Fresh produce is usually consumed raw, and there is no kill step to eliminate pathogens. However, the fresh produce industry is in need of a kill step to ensure the safety of produce. Ionizing irradiation is known to effectively eliminate human pathogens such as *E. coli* O157:H7 on fresh produce (Niemira and Fan 2006). However, the commercial application of irradiation to fresh produce is still limited partially due to concerns about possible damages to sensory and nutritional quality. There have been many studies concerning the irradiation of fresh and fresh-cut fruits and vegetables. However, most of the studies focused on only 1 or 2 fruits and vegetables. There is no comprehensive study of major fresh-cut vegetables in a single study. In addition, fresh-cut produce was not properly packaged in some studies. Commercially, some fresh-cut vegetables are packaged in modified atmosphere packages (MAP) while others are packaged in perforated packages that allow easy exchange of atmosphere. The *D*-values (the amount of radiation energy required to inactivate 90% of specific pathogens) of *E. coli* O157:H7 on fresh-cut vegetables were mostly between 0.12 and 0.20 kGy (Niemira and others 2002; Foley and others 2004; Niemira and Fan 2006). Therefore, a dose of 1 kGy irradiation can achieve at least a 5 log reduction of *E. coli* O157:H7, surface inoculated on fresh produce, although the internalized pathogens may better able to survive irradiation than those on the surface (Niemira 2007). In the recent proposal of labeling changes (FDA 2007), FDA expressed interest in information on whether the control of foodborne pathogens by irradiation changes the characteristics of food in a way that is outside of the normal variability of the food and would therefore require additional labeling to inform the consumer of such change. The objective of this study was to study the effects of 1 kGy irradiation on the appearance, texture, aroma, and vitamin C content of major fresh-cut vegetables packaged in either MAP or air.

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Materials and Methods

Source of vegetables

Thirteen fresh-cut vegetables were used: iceberg, romaine, red leaf, and green leaf lettuce (*Lactuca sativa* L.), cilantro (*Coriandrum sativum*), parsley (*Petroselinum hortense*), green onion (*Allium fistulosum*), carrot (*Daucus carota* L.), broccoli (*Brassica oleracea* L. var. italica Plen), red cabbage (*Brassica oleracea*, Capitata group), spinach (*Spinacia oleracea*), celery (*Apium graveolens* L.), and tomato (*Lycopersicon esculentum* L.). These vegetables were chosen because of their economic importance, or their possible association with contamination by foodborne pathogens and

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outbreaks of illnesses, or both. The fresh-cut vegetables were either prepared in the laboratory from the whole, uncut commodity or purchased as a fresh-cut product from distributors through local supermarkets.

Preparation of fresh-cut vegetables

Packaged fresh-cut broccoli, shredded carrots and red cabbage, iceberg and romaine lettuce, and spinach were obtained from local supermarkets and used without further preparation. Only products that had at least 7 d of shelf life (according to the sell-by date) were purchased. Cilantro and parsley (approximately 5 kg) purchased from a wholesale market were washed in 20 L water first, cut into 2 to 3 cm segments in length, and dipped in chlorine solution (100 ppm) for 2 min, followed by rinsing in 20 L deionized water. Green onions were cut into 1 to 2 cm segments, and celery (stalks) was cut into approximately 1 cm segments before being treated with chlorine solution (100 ppm) and rinsed with water. In addition to the prepackaged iceberg lettuce, fresh-cut iceberg lettuce was also prepared in the laboratory and stored in perforated bags. Whole iceberg, red leaf, and green leaf lettuces were cut into 3×3 cm pieces and dipped in 100 ppm chlorine solution for 2 min before being rinsed in water. The fresh-cut samples prepared in the lab were packaged into 2 perforated (7 mm in diameter) zipper bags (16.5×14.9 cm) (S. C. Johnson and Sons Inc., Racine, Wis., U.S.A). Tomatoes were dipped into 100 ppm chlorine solution for 2 min before being sliced (0.3 cm thickness) using a sharp knife, and packaged in 16-oz clamshell (polystyrene) containers (200 g each container). The amounts of samples in each package varied (depending on the bulk density of the vegetables) as follows: tomato, 175 g; red and green leaf lettuce, 105 g; iceberg lettuce, 150 g, green onions, 130 g; parsley, 110 g; cilantro, 105 g; celery, 150 g. All samples were cooled on ice for 3 h before being irradiated with gamma rays at a dose of 0 kGy (nonirradiated control) or 1 kGy at 4 °C. There were 4 replicates for each treatment per sampling day.

MAP and storage

The following vegetables were packaged in modified atmosphere: broccoli, carrots, iceberg and romaine lettuce, red cabbage, spinach, and tomato. For all the vegetables except tomato, atmosphere had already been established in the packages by commercial processors when the samples were purchased. The nature of package material was unknown because they were considered proprietary. For tomato, modified atmosphere in the polystyrene clamshell was established as a result of respiration (passive MAP). The rest of the fresh-cut vegetables and iceberg lettuce were packaged in perforated film bags that freely allowed gas exchange.

After irradiation of the packaged vegetables, all samples were stored at 4 °C for 14 d. Gas composition in the packages were measured first followed by evaluation of aroma, appearance, texture, and vitamin C content of the samples after 1- and 14-d storage.

Irradiation and dosimetry

The samples were irradiated using a self-contained cesium-137 gamma radiation source (Lockheed Georgia Co., Marietta, Ga., U.S.A.) with a dose rate of 0.089 kGy/min. Variations in radiation dose absorption were minimized by placing the samples within a uniform area of the radiation field, by irradiating them within a polypropylene container (4 mm wall) to absorb Compton electrons, and by using the same geometry for sample irradiation during the entire study. During irradiation, temperature (4 ± 2 °C) in the radiation chamber was controlled by flushing the gas phase of liquid nitrogen into the upper portion of the chamber. To eliminate possible effects of nitrogen flushing during irradiation, bags of all treatments (including the controls) were placed in the chamber with nitrogen flushing for the same total period. Routine dosimetry was performed using 5-mm-dia alanine pellets (Bruker Inc., Billerica, Mass., U.S.A.). The pellets were placed in 1.2 mL cryogenic vials (Nalgene, Rochester, N.Y., U.S.A.), and the cryogenic vials were placed with the samples prior to irradiation. Alanine pellets were read using a Bruker EMS 104 EPR analyzer and compared with a standard curve. Actual dose was typically within 5% of the targeted doses. Maximum/minimum dose ratio was 1.1.

Evaluation of appearance and aroma

Evaluations of aroma and appearance were conducted using a 9-point category scale (Kader and others 1983; Loaiza-Velarde and others 1996). For aroma, judges opened the packages, sniffed the headspace, and gave a rating using a 9-point scale: 9 = strong, characteristic odor; 7 = slightly "flat"; 5 = bland, faint odor or detectable off-odor; 3 = mild off-odors; 1 = distinct rotten smell or other strong off-odors. For visual quality, the description for the scales was 9 = excellent quality, essentially free from defects, fresh appearing; 7 = good quality, minor defects; 5 = fair quality, slightly to moderately objectionable defects, lower limit of sale appeal; 3 = poor quality, excessive defects; 1 = extremely poor quality, not usable. Pictures that corresponded to each scale point were available for judges to rate the samples. Three experienced judges independently performed subjective assessments. For evaluating aroma, the 1st judge opened the packages and sniffed the headspace of a sample and gave it to the second and then to the 3rd judge right away without any delay. Thus, each judge evaluated all samples for aroma and appearance. There were 4 replicated packages for each treatment/sampling day.

Headspace analysis

Gases within the sealed packages were sampled to determine the levels of CO_2 and O_2 after 1 and 14 d after irradiation. To measure the atmosphere, a 0.5 mL headspace sample was withdrawn from the bags using a syringe by piercing the films or trays with a fine hypodermic needle. The sampling hole was resealed with a patch of electrical tape, and the contents of the packages were used in subsequent quality analysis. The gas samples were then injected into a Gow-Mac Series 580 gas chromatograph (Gow-Mac Instrument, Bridgewater, N.J., U.S.A.) equipped with a 183 cm CTR I column (Alltech Associates Inc., Deerfield, Ill., U.S.A.) and a thermal conductivity detector. The CTR I column consists of an outer column (0.64 cm i.d.) packed with an activated molecular sieve and an inner column (0.32 cm i.d.) packed with a porous polymer mixture. The injector, oven, and detector temperatures were held at ambient temperature (23 to 25 °C). The carrier gas was helium with a flow rate at 120 mL/min. CO_2 and O_2 levels were calculated by comparing the peak heights of samples to those of a standard gas mix of 3% CO_2 and 17% O_2.

Texture measurement

Texture was determined using the TA-XT2i texture analyzer (Texture Technology Corp., Scarsdale, N.Y., U.S.A.) with specified shearing devices for different vegetables. To measure texture of broccoli, similar diameters (1.5 ± 0.2 cm) of broccoli stem were first transversely cut into 1-cm-long pieces. To measure texture, the pieces were turned on their sides so that the TA-43 blade with flat 3 mm end longitudinally cut through the pieces. Celery texture was similarly measured after being cut into 1-cm-long pieces. Five pieces of broccoli stem and celery from each bag were used. The total number of measurements per treatment was 20. For carrots, 5 shredded carrot strips ($3 \times 3 \times 77$ mm) from each bag were cut using a

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Warner–Bratzler shear blade. For red cabbage, green and red leaf lettuce, iceberg and romaine lettuce, and spinach 15 g samples were placed into a Kramer Shear press with 5 blades. For cilantro and parsley, 10 g of the sample were placed into the press, while for tomato, 50 g samples were placed into the press. For green onions, 3 g samples were placed into a mini Kramer Shear press. For all the samples, the 5 flat plunger devices were set at 70 mm (Kramer) or 20 mm (mini Kramer) from the bottom of the rectangular sample holding box, moved down to the sample at a speed of 2 mm/s, compressed the samples through the 5 slots, and stopped when it reached 5 mm below the bottom of the holding box. Forces over time were recorded using the texture expert software (version 1.22, Texture Technology Corp.). The maximum shear force and the area under the force–time curve were then calculated.

Vitamin C analysis

Vitamin C (ascorbic acid [AA] plus dehydroascorbic acid) was analyzed as described previously (Fan and others 2003c). Samples (10 g) were homogenized with 20 mL 5% (62.5 mM) metaphosphoric acid (MPA) using a homogenizer (Virtishear, Virtis, Gardiner, N.Y., U.S.A.) at a speed setting of 70 for 1 min. The homogenate was filtered through 4 layers of cheesecloth, and then the filtrate was centrifuged at 10000 × *g* for 10 min at 4 °C in a Sorvall RC2-B refrigerated centrifuge (Kendro Laboratory Products, Newtown, Conn., U.S.A.). To reduce dehydroascorbic acid in the supernatant to AA, 1 mL aliquot supernatant (diluted when needed, depending on the amount of AA) was added to 0.16 mL of 30 mM DL-homocysteine solution, and the pH was adjusted to 6.5 to 7.0 by slow addition of approximately 0.13 mL 2.6 M dipotassium hydrogen phosphate. After 30 min at 23 °C, the reaction was stopped by addition of 5% (w/v) MPA to 2 mL. The mixture was filtered through a 0.45 μm PVDF Durapore Millex-HV syringe filter (Millipore Corp., Bedford, Mass., U.S.A.). The filtered samples were placed in 2 mL vials and analyzed using Hewlett Packard Ti-series 1050 HPLC system (Agilent Technologies, Palo Alto, Calif., U.S.A.). The HPLC system consists of an autosampler, an integral photodiode-array detector, an autoinjector, and a Hewlett-Packard Rev. A02. 05 Chemstation. Injection volume was 20 μL. Separation of compounds was achieved with an Aminex HPX-87H organic acids column (300 × 7.8 mm) fitted with a microguard cation H+ by elution with a mobile phase of 5 mM sulfuric acid at a flow rate of 0.5 mL/min. Column temperature was maintained at 30 °C using a column heater (Bio-Rad Laboratories, Hercules, Calif., U.S.A.). AA was monitored at 245 nm, and the sample AA content was calculated from an AA standard.

Statistical analysis

The experiment was conducted using a complete random design. The experiments were repeated 4 times. Data were subjected to statistical analysis using SAS ver. 8e (SAS Inst. Inc., Raleigh, N.C., U.S.A.). The least significant difference (LSD) test was performed using the general linear models (GLM) procedure.

Results and Discussion

Headspace atmosphere in the packages

One day after irradiation, packages of irradiated broccoli had significantly ($P < 0.05$) lower O_2 levels (3.5%) than the controls (6.7%) (Table 1). There were no other differences in O_2 and CO_2 levels in the other packages of fresh-cut vegetables between irradiated and control samples. After 14 d of storage, the O_2 and CO_2 levels were similar among the irradiated and nonirradiated samples except for irradiated carrots, which had higher CO_2 and lower O_2 than the control samples, which were completely rotted. The O_2 levels in the packages of spinach and tomato were not much different from those in air. O_2 levels were below 10% in the packages of broccoli and romaine and iceberg lettuce while the CO_2 levels in the packages were between 5% and 12%. The low O_2 level in the irradiated broccoli observed at day 1 indicated that irradiation might increase respiration rate. However, the increases were temporary. During storage, the O_2 and CO_2 levels did not change much in the packages of any vegetable except tomato whose O_2 levels decreased.

Appearance

One day after irradiation, there was no significant ($P < 0.05$) difference in the appearance between the irradiated samples and the corresponding controls for any of the vegetables (Table 2). After 14-d storage, irradiated carrots, celery, cilantro, and green onions had significantly better visual quality than the corresponding controls (Table 2). The control samples of these vegetables developed decay or browning. Control green onions were completely rotted. Irradiation reduced the development of decay or browning in these fresh-cut samples. It is well known that irradiation reduces the population of microorganisms on fresh produce. For example, Koorapati and others (2004) showed that irradiation at doses above

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Table 1 — O_2 and CO_2 levels (%) in the headspace of modified atmosphere packages after 1- and 14-d storage at 4 °C.

	Day 1		Day 14	
Vegetables	0 kGy	1 kGy	0 kGy	1 kGy
O_2				
Broccoli	6.7 ± 1.3 a	3.5 ± 1.2 b	8.1 ± 3.5 a	6.7 ± 0.9 a
Carrots	19.5 ± 1.8 a	19.9 ± 0.7 a	12.8 ± 5.0 b	18.6 ± 2.3 a
Iceberg lettuce	1.1 ± 0.6 a	1.9 ± 2.5 a	1.0 ± 0.4 a	1.2 ± 0.6 a
Red cabbage	17.2 ± 1.6 a	16.7 ± 1.8 a	12.1 ± 5.4 a	16.7 ± 4.4 a
Romaine lettuce	5.7 ± 5.2 a	2.2 ± 1.3 a	5.1 ± 6.8 a	2.8 ± 4.4 a
Spinach	19.8 ± 1.3 a	20.1 ± 1.8 a	19.8 ± 0.8 a	18.9 ± 0.8 a
Tomato	21.3 ± 1.8 a	22.2 ± 0.7 a	17.5 ± 1.3 b	18.4 ± 1.7 b
CO_2				
Broccoli	4.7 ± 0.4 ab	5.4 ± 0.6 a	4.6 ± 0.7 b	5.2 ± 0.4 b
Carrots	2.9 ± 1.1 b	2.7 ± 0.9 b	10.0 ± 3.3 a	4.3 ± 2.7 b
Iceberg lettuce	7.2 ± 0.7 a	7.7 ± 0.6 a	7.8 ± 1.5 a	7.7 ± 0.7 a
Red cabbage	3.8 ± 0.5 a	4.4 ± 1.3 a	8.6 ± 4.5 a	4.6 ± 4.5 a
Romaine lettuce	5.7 ± 0.8 b	7.8 ± 0.8 b	8.6 ± 3.0 ab	11.8 ± 2.8 a
Spinach	2.3 ± 0.5 a	3.0 ± 0.5 a	2.5 ± 0.7 a	2.7 ± 0.3 a
Tomato	2.1 ± 0.2 a	2.4 ± 0.3 a	3.0 ± 0.4 a	1.9 ± 1.3 a

The numbers are means of 4 replicates followed by standard deviations. Means with the same letter are not significantly different (LSD, $P < 0.05$).

0.5 kGy prevented microbial-induced browning and blotching of sliced mushrooms. Irradiated iceberg lettuce stored in air had a lower score of visual quality than the control. The lower score was due to irradiation-induced enzymatic browning. When iceberg lettuce was stored in MAP, the irradiated sample had better appearance than the control.

Texture

Texture was expressed by both the maximum shear force and the area under the force–time curve. The area under the force–time curve represented the total work required to cut through the samples. Neither maximum shear force nor the area of most vegetables was consistently affected by irradiation. One day after irradiation, irradiation at 1 kGy did not significantly ($P < 0.05$) affect texture of any fresh-cut vegetables except broccoli, cilantro, and green onions (Table 3). The area under the force–time curve for the irradiated broccoli was larger than the control while the area for irradiated green onions and cilantro was smaller than the corresponding controls.

After 14d storage, 1 kGy irradiation did not have any effect on texture of any vegetables except cilantro. The area under the force–time curve for cilantro was lower than the irradiated samples (Table 3). The deterioration in texture in the control cilantro was probably due to the decay and senescence of the sample. Unlike on day 1, irradiated broccoli had similar texture as the control after 14 d storage. The control green onions were completely rotted; therefore, no measurements of texture could be performed on the control sample.

Aroma

One day after irradiation, irradiated samples had similar aroma scores as controls except for iceberg lettuce in MAP, broccoli, and tomatoes. Irradiation induced off-odors in the packaged iceberg lettuce, tomato, and broccoli (Table 4). The off-odors in tomato and iceberg lettuce in commercial MAP may be produced from packaging materials because we found that irradiated package material without produce produced similar off-odors. Therefore, not all packaging materials currently used by the fresh-cut industry are suitable for irradiation. New packaging materials containing adjuvants (antioxidants, stabilizers, and so on) may be developed to eliminate the formation of off-odors. The off-odors in the irradiated broccoli had characteristics of sulfur compounds. It has been shown that irradiation induced formation of volatile sulfur compounds in other products (Fan and others 2002; Lee and Ahn 2003; Fan 2004). It is also known that broccoli can produce volatile sulfur compounds under stress conditions such as anaerobic

Table 2—Appearance of nonirradiated and irradiated fresh-cut vegetables after 1- and 14-d storage at 4 °C.

		Day 1		Day 14	
Vegetables	Atmosphere	0 kGy	1 kGy	0 kGy	1 kGy
Broccoli	MAP	8.1 ± 1.1 a	8.3 ± 0.6 a	5.6 ± 1.1 b	6.0 ± 0.7 b
Carrots	MAP	8.5 ± 0.8 a	8.4 ± 0.5 a	1.6 ± 0.7 c	4.3 ± 1.7 b
Celery	Air	8.5 ± 0.6 a	8.3 ± 0.6 a	3.8 ± 1.5 c	5.7 ± 1.5 b
Cilantro	Air	8.2 ± 0.7 a	8.2 ± 0.3 a	1.0 ± 0.0 c	4.4 ± 0.6 b
Green leaf lettuce	Air	8.5 ± 0.7 a	8.3 ± 0.9 a	6.1 ± 0.6 b	5.6 ± 0.8 b
Green onions	Air	8.4 ± 0.9 a	8.0 ± 1.2 a	1.0 ± 0.0 c	2.9 ± 0.5 b
Iceberg lettuce	MAP	9.0 ± 0.0 a	8.9 ± 0.3 a	6.8 ± 1.5 c	7.9 ± 1.4 b
Iceberg lettuce	Air	8.8 ± 0.4 a	8.3 ± 0.9 a	4.4 ± 1.0 b	1.5 ± 0.7 c
Parsley	Air	8.2 ± 0.7 a	8.2 ± 0.2 a	5.1 ± 1.0 b	5.3 ± 1.1 b
Red cabbage	MAP	8.4 ± 0.5 a	8.3 ± 0.6 a	6.4 ± 0.6 b	6.5 ± 0.8 b
Red leaf lettuce	Air	8.5 ± 0.5 a	8.6 ± 0.5 a	4.7 ± 0.7 b	4.3 ± 0.6 b
Romaine lettuce	MAP	8.4 ± 0.8 a	8.4 ± 0.5 a	7.0 ± 0.9 b	7.0 ± 0.9 b
Spinach	MAP	8.7 ± 0.5 a	8.4 ± 0.5 a	7.2 ± 0.7 a	7.4 ± 0.6 a
Tomato	MAP	7.7 ± 1.0 a	7.3 ± 1.1 a	5.4 ± 0.5 b	5.7 ± 0.5 b

The numbers are means of 4 replicates followed by standard deviations. Means with the same letter are not significantly different (LSD, $P < 0.05$).
MAP = modified atmosphere packaging.
9 = excellent quality, essentially free from defects, fresh appearing; 7 = good quality, minor defects; 5 = fair quality, slightly to moderately objectionable defects, lower limit of sale appeal; 3 = poor quality, excessive defects; 1 = extremely poor quality, not usable.

Table 3—Texture (area under the time–force curves/1000) of nonirradiated and irradiated fresh-cut vegetables after 1- and 14-d storage at 4 °C.

		Day 1		Day 14	
Vegetables	Atmosphere	0 kGy	1 kGy	0 kGy	1 kGy
Broccoli	MAP	7.72 ± 1.68 b	9.38 ± 2.35 a	6.62 ± 2.16 bc	5.47 ± 1.76 c
Carrots	MAP	1.06 ± 0.32 a	1.07 ± 0.28 a	0.90 ± 0.29 a	1.09 ± 0.43 a
Celery	Air	3.20 ± 1.24 a	3.38 ± 1.43 a	3.20 ± 0.89 a	3.15 ± 1.25 a
Cilantro	Air	100.12 ± 18.11 a	78.35 ± 9.36 b	54.67 ± 20.02 c	80.13 ± 9.59 b
Green leaf lettuce	Air	128.35 ± 16.05 a	114.01 ± 13.72 a	128.38 ± 15.12 a	125.19 ± 16.79 a
Green onions	Air	76.27 ± 8.80 a	64.53 ± 8.48 b	NT	71.75 ± 10.97 ab
Iceberg lettuce	MAP	21.06 ± 1.94 a	21.12 ± 2.28 a	22.19 ± 2.98 a	21.12 ± 1.35 a
Iceberg lettuce	Air	74.14 ± 10.68 b	79.24 ± 5.75 b	89.43 ± 11.05 a	83.66 ± 10.38 a
Parsley	Air	102.24 ± 14.20 a	113.06 ± 23.36 a	120.18 ± 16.76 a	116.23 ± 17.42 a
Red cabbage	MAP	145.46 ± 17.13 a	144.51 ± 13.59 a	147.27 ± 23.85 a	138.84 ± 12.14 a
Red leaf lettuce	Air	85.89 ± 9.19 a	72.02 ± 17.89 a	80.72 ± 13.42 a	84.67 ± 13.53 a
Romaine lettuce	MAP	120.90 ± 21.27 a	125.61 ± 24.04 a	126.54 ± 8.54 a	116.76 ± 17.81 a
Spinach	MAP	136.87 ± 11.67 a	121.08 ± 11.67 a	132.31 ± 8.01 a	122.77 ± 14.52 a
Tomato	MAP	56.21 ± 15.82 a	46.41 ± 9.07 a	47.29 ± 10.37 a	44.38 ± 9.80 a

The numbers are means of 4 replicates followed by standard deviations. Means with the same letter are not significantly different (LSD, $P < 0.05$).
MAP = modified atmosphere packaging; NT = not tested.

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atmosphere (Chin and Lindsay 1993). The O_2 levels in the irradiated broccoli were lower than those in the control samples. Therefore, the off-odor in the broccoli could be due to anaerobic metabolism in the broccoli or due to irradiation-induced volatile sulfur compounds from amino acids or proteins, similar to those in meat products.

After 14 d storage, the aroma scores of irradiated carrots, cilantro, green onions, parsley, and red leaf lettuce were higher than those of controls, while irradiated iceberg lettuce stored in air and tomato had a lower aroma score than the controls (Table 4). The lower score in the irradiated iceberg lettuce sample is probably related to the low score (severe browning) in appearance (Table 2), while volatiles from packages may contribute to the off-odors of tomatoes. For the other vegetables, irradiation had no effect on the aroma scores. The lower scores appear to be related to decay or browning. For example, control green onions, which were completely rotted, had a lower aroma score. Similarly, some of the control carrots and cilantro also decayed and had low aroma scores.

Vitamin C

One day after irradiation, there were no significant differences in vitamin C content between the irradiated samples and corresponding controls for the fresh-cut vegetables except for iceberg lettuce stored in MAP, green and red leaf lettuce, and spinach (Table 5). The losses in vitamin C content of the iceberg, green, and red leaf lettuce were 22%, 24%, and 47%, respectively. After 14-d storage, irradiated green leaf lettuce, iceberg lettuce stored in air, red leaf lettuce, spinach, and tomatoes had significantly ($P < 0.05$) lower vitamin C content than the corresponding controls (Table 5). The losses ranged from 23% for tomato to 53% for red leaf lettuce irradiation did not affect the vitamin C content of other samples. The control green onions were completely rotted, and vitamin C was not measured for these samples. Among the vegetables, only irradiated green and red lettuce had lower vitamin C contents than controls at both day 1 and day 14. It is known that ascorbic acid is sensitive to irradiation, converting it to dehydroascorbic acid (Simic 1983; Thayer and others 1991). However, both ascorbic acid and dehydroascorbic acid are biologically active. The loss of vitamin C was observed only in a few samples. High levels of antioxidants in some samples may quench free radicals generated in the samples by irradiation, avoiding the reaction of free radical with ascorbic acid and thereby preventing the degradation of ascorbic acid. There was considerable variation in the levels of vitamin C among the vegetables. For example, broccoli had more than 40 times higher vitamin C content than iceberg lettuce. Furthermore, vitamin C content levels generally decreased during storage for most vegetables. The changes in vitamin C content due to storage and variety differences may be larger than the losses caused by irradiation. In

Table 4—Aroma (9 to 1) of nonirradiated and irradiated fresh-cut vegetables after 1- and 14-d storage at 4 °C.

		Day 1		Day 14	
Vegetables	Atmosphere	0 kGy	1 kGy	0 kGy	1 kGy
Broccoli	MAP	7.9 ± 0.9 a	6.8 ± 1.4 b	5.8 ± 0.8 c	6.0 ± 0.6 bc
Carrots	MAP	8.5 ± 0.7 a	8.2 ± 0.7 a	2.8 ± 1.4 c	4.6 ± 0.9 b
Celery	Air	8.5 ± 0.5 a	8.0 ± 0.3 a	4.3 ± 1.2 b	4.7 ± 0.8 b
Cilantro	Air	8.3 ± 0.5 a	7.8 ± 0.6 a	2.2 ± 1.4 c	4.5 ± 1.0 b
Green leaf lettuce	Air	7.8 ± 1.1 a	7.4 ± 0.6 a	5.9 ± 0.8 b	5.5 ± 0.8 b
Green onions	Air	8.3 ± 0.5 a	8.2 ± 0.5 a	2.0 ± 1.1 c	3.7 ± 0.9 b
Iceberg lettuce	MAP	8.2 ± 0.6 a	7.3 ± 1.3 b	7.2 ± 1.2 b	7.0 ± 1.1 b
Iceberg lettuce	Air	7.8 ± 1.1 a	7.3 ± 0.7 a	5.6 ± 0.5 b	4.2 ± 0.8 c
Parsley	Air	8.1 ± 0.8 a	7.3 ± 0.7 a	4.0 ± 0.7 c	5.0 ± 0.8 b
Red cabbage	MAP	8.5 ± 0.5 a	8.2 ± 0.4 a	6.3 ± 0.6 b	5.9 ± 0.8 b
Red leaf lettuce	Air	7.5 ± 1.3 a	7.2 ± 1.0 a	5.0 ± 0.1 b	5.0 ± 0.1 b
Romaine lettuce	MAP	7.6 ± 1.4 a	7.4 ± 0.7 ab	6.2 ± 1.6 c	6.5 ± 1.2 bc
Spinach	MAP	7.0 ± 0.9 ab	7.3 ± 1.0 a	6.8 ± 0.7 ab	6.5 ± 0.6 ba
Tomato	MAP	8.3 ± 0.5 a	6.3 ± 1.1 b	6.0 ± 0.6 b	5.2 ± 1.1 c

The numbers are means of 4 replicates followed by standard deviations. Means with the same letter are not significantly different (LSD, $P < 0.05$).
MAP = modified atmosphere packaging.
9 = strong, characteristic odor; 7 = slightly "flat"; 5 = bland, faint odor or detectable off-odor; 3 = mild off-odors; 1 = distinct rotten smell or other strong off-odors.

Table 5—Total vitamin C content (μg/g fresh weight) of nonirradiated and irradiated fresh-cut vegetables after 1- and 14-d at 4 °C.

		Day 1		Day 14	
Vegetables	Atmosphere	0 kGy	1 kGy	0 kGy	1 kGy
Broccoli	MAP	925.9 ± 71.7 a	902.3 ± 101.3 a	854.9 ± 76.1 a	854.8 ± 11.2 a
Carrots	MAP	92.6 ± 11.7 a	88.6 ± 3.9 a	55.4 ± 36.1 b	59.1 ± 5.3 b
Celery	Air	50.2 ± 9.5 a	49.8 ± 7.2 a	42.0 ± 4.2 ab	32.5 ± 0.9 b
Cilantro	Air	528.5 ± 40.3 a	537.9 ± 81.9 a	115.5 ± 44.7 b	157.2 ± 38.6 b
Green leaf lettuce	Air	88.8 ± 14.2 a	67.1 ± 15.9 b	52.8 ± 10.1 b	28.2 ± 8.2 c
Green onions	Air	117.1 ± 11.0 a	129.1 ± 7.0 a	NT	84.4 ± 7.2 b
Iceberg lettuce	MAP	30.3 ± 2.8 a	16.8 ± 5.0 b	15.2 ± 3.6 b	12.9 ± 4.5 b
Iceberg lettuce	Air	20.7 ± 3.6 a	16.1 ± 3.8 ab	21.7 ± 6.9 a	10.9 ± 2.6 b
Parsley	Air	1148.8 ± 90.6 a	1086.5 ± 169.5 a	614.5 ± 118.8 b	533.9 ± 41.6 b
Red cabbage	MAP	681.3 ± 31.8 a	632.1 ± 29.9 ab	623.9 ± 44.2 b	652.8 ± 21.9 ab
Red leaf lettuce	Air	74.5 ± 9.1 a	39.1 ± 5.9 b	33.7 ± 6.3 b	15.7 ± 1.2 c
Romaine lettuce	MAP	38.1 ± 14.3 a	47.6 ± 3.5 a	44.8 ± 17.9 a	28.9 ± 15.8 a
Spinach	MAP	264.8 ± 37.9 a	198.7 ± 34.1 a	198.2 ± 55.8 a	68.6 ± 51.5 b
Tomato	MAP	147.6 ± 14.7 a	132.8 ± 16.1 a	144.9 ± 5.1 a	111.4 ± 16.2 b

The numbers are means of 4 replicates followed by standard deviations. Means with the same letter are not significantly different (LSD, $P < 0.05$).
MAP = modified atmosphere packaging; NT = not tested.

S: Sensory & Food Quality

addition, ascorbic acid often constitutes a very small portion of the total antioxidants in some vegetables. Our earlier results showed that irradiation did not reduce the amount of total antioxidants (Fan 2005). On the contrary, irradiation increased antioxidant capacity of several vegetables, presumably due to increased synthesis of phenolic compounds.

After 14 d of storage, the scores of some fresh-cut vegetables (both 1 kGy and nonirradiated samples) fell below 5, making those products unmarketable. Nevertheless, many irradiated samples had better appearance and aroma scores compared with the nonirradiated controls after 14 d of storage, suggesting that irradiation extended the shelf life of some vegetables. However, it is unclear how many days of shelf life was extended for those vegetables. More studies with much more sampling frequencies may be conducted to find out the exact days of shelf life extension for the specific vegetables. In addition, a subjective sensory evaluation was conducted in the present study using the preset scaling systems. Consumer or trained panels with large numbers of panelists may be employed in future studies to study the consumer perception of irradiated fresh-cut produce.

Our results suggest that most of the vegetables examined tolerated a radiation dose of 1 kGy, which appears to be in agreement with many previous studies that often focused on certain individual quality attributes. For example, it was found that irradiation at 1.0 and 1.5 kGy reduced the development of decay and off-odor, improved visual quality, and preserved the color of green onions (Fan and others 2003a; Kim and others 2005). Similarly, irradiation of fresh-cut lettuce in modified atmosphere packages at a dose of 1 kGy maintained visual quality, while higher doses of irradiation induced electrolyte leakage and soggy appearance (Fan and Sokorai 2002). Furthermore, it was found that 1 kGy irradiation preserved firmness and color of sliced mushroom (Koorapati and others 2004) and physicochemical properties of carrots (Lafortune and others 2005). Some vegetables such as cut Romaine lettuce and diced tomato may suffer a loss in texture at a dose of 1 kGy (Prakash and others 2000, 2002), while some fresh-cut vegetables such as cilantro may tolerate up to 2 kGy (Fan and others 2003b) or even 3.85 kGy irradiation (Foley and others 2004).

It should be pointed out that there are limitations in this study. While about half of the fresh-cut vegetables were irradiated in the original packaging from a commercial processing facility, the nature of packaging materials was unknown. In addition, the commercially processed fresh-cut vegetables were irradiated days after processing. Ideally, the fresh-cut produce should be irradiated as soon as possible after packaging, prior to distribution to retail or whole market. Fresh-cut produce that is shipped to an off-site irradiation facility should be held in an intact cold chain with other good handling practices during the 1 to 2 d required for the transshipment to avoid possibility of quality loss and microbial growth.

It appears that modified atmosphere packaging can affect the response of produce to irradiation. For example, iceberg lettuce packaged in air developed accelerated browning after irradiation, while irradiation of samples stored in MAP did not increase tissue browning.

Conclusions

Our result showed that the appearance, texture, and aroma of most of the fresh-cut vegetables examined were not negatively affected by the 1 kGy irradiation when stored in air or MAP. The appearance and aroma of many irradiated vegetables were better than that of the corresponding controls after 14 d storage, probably due to the reduction of decay and browning. However, vitamin C content was reduced by irradiation in some vegetables, particularly green and red leaf lettuce. Overall, our results demonstrated that most fresh-cut vegetables can tolerate 1 kGy irradiation without deterioration in quality.

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